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DESIGN OF NON METALLIC SHIP HULLS FOR STRENGTH AND SUSTAINABILITY

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ABSTRACT

Fibre Reinforced Polymers (FRP) have been used in the construction of marine composite vessels due to their inherent advantages over metal counterparts. Strength and Sustainability of such vessels are of extreme concern in today's world which in turn is directly connected with the strength and environmental impact of the composite laminate materials used for their construction. In this paper a strength index and a sustainability index has been developed for nine commonly used non metallic composite laminate materials used for ship hull construction. Based on these indices a two dimensional assessment of composite materials has been done and a design philosophy based on strength and sustainability has been proposed.

KEYWORDS: Fibre Reinforced Polymer, Strength Index, Sustainability Index, Design for strength and sustainability.

A_m = cross-sectional area of matrix in a ply

E_1 = elastic modulus of laminate in the longitudinal direction

E_f = elastic modulus of fibre

E_m = elastic modulus of matrix

V_f = volume fraction of fibre in a ply

V_m = volume fraction of matrix in a ply

INTRODUCTION

Fibre Reinforced Polymer (FRP) boatbuilding began after World War II. After FRP boat building gathered momentum, FRP constructions were taken up for bigger marine vessels like mine counter mine vessels, corvettes etc. Advantages of FRP composite materials over steel and other metals used for the construction of marine structures are high specific strength, high specific stiffness, good fatigue properties, low magnetic properties or high stealth properties, resistance to corrosion and manufacturability to near net-shape. The structures made of composites have larger life span and need low maintenance. One of the main advantages of construction using composite materials is the ability to choose the material, laminate and manufacturing method to suit the design requirements. Composite materials are engineered materials made from two or more constituent materials that are combined at a macroscopic level. When both the matrix and fibre are not of metallic origin, such composites are called as non metallic composites. Glass Fibre Reinforced Polymers (GFRP), Carbon Fibre Reinforced Polymers (CFRP) and Aramid Fibre Reinforced Polymers (AFRP) are

common non metallic composite materials used for marine structural applications. These are used in laminate form in ship construction.

FIBRES AND RESINS USED FOR NON METALLIC HULL CONSTRUCTION

Glass fibres account for over 90% of the fibres used in reinforced plastics because they are inexpensive to produce and have relatively good strength to weight characteristics. Glass fibres exhibit excellent tensile strength, good chemical resistance and processability. Carbon fibres offer the highest strength and stiffness of all commonly used reinforcement fibres. These fibres are extremely stiff, strong, and light. These fibres are not subjected to stress rupture or stress corrosion, as glass and aramid. The major drawback of carbon fibres is their relative cost, which is a function of energy intensive manufacturing process. Aramid fibres possess low weight, high tensile strength and modulus, better impact and fatigue resistance than other fibres. Compressive performance of aramids is not as good as glass. Although impact resistance of glass fibre is more than that of aramid fibre, time taken by aramid fibre for complete failure is more than that of glass fibre. Polyester Resins are the simplest, most economical, easiest to use resin systems. They exhibit good chemical resistance. The marine industry has generally based its structures on polyester resin. Vinyl Ester Resins have similar handling and performance characteristics as polyesters. Vinyl esters have higher elongation to break capacity than polyesters, which makes them tougher. Epoxy Resins show the best performance characteristics of all the resins used in the marine industry. The high cost of epoxies and handling difficulties have limited their use in large marine structures.

STRENGTH OF COMPOSITE LAMINATES

Mohan et.al.[2013] Reddy et.al.[2013] and Akhbari et.al. [2008] have conducted buckling tests on various composites. FE analysis has been carried out using various finite element commercial softwares like MSC. Patran/Nastran, ANSYS and ABACUS. When composite panels are stressed, they fail one ply at a time, causing a change in strength and stiffness, leading ultimately to catastrophic failure. Composite materials exhibit very complex failure mechanisms under static and fatigue loading because of anisotropic characteristics in their strength and stiffness. The degradation rates are higher in Low Cycle Fatigue (LCF) when compared to High Cycle Fatigue (HCF). LCF damage is dominated by the random fibre breakage and matrix cracks that grow around broken fibres. The introduction of composite materials into the shipping industry has led to lighter, stiffer and faster vessels which require increased impact performance. Impact energy levels can exceed the capabilities of the structure, leading to catastrophic failure. Zike et.al.[2011], Akin and Senel[2010], Wisheart and Richardson [1996], Norman [1975] and Sun and Yang [1980] have conducted impact studies on glass/polyester, E-glass/epoxy, aramid/epoxy, and carbon/epoxy composites. Mixed views exist as to the effects of fatigue load and amount of energy absorbed by the laminate and structural damage caused , due to the variation of constituent materials, fibre orientations, fabrication techniques and stacking sequences, which make each composite, behave differently. It was found that there is variation in buckling load with change in aspect ratio, change in the fibre orientation, change in constituents and type of the openings in the plates.

SUSTAINABILITY OF NON METALLIC COMPOSITE MATERIALS

When compared to steel vessels, the world of marine composite vessels is extremely concerned with the sustainability of the vessels which in turn is directly connected with the environmental impact of the composite laminate materials used for their construction. Composite materials have inherent benefits that make it a sustainable material. These benefits are durability, high insulation, high strength to weight ratio, re use capability, can incorporate recycle content and

can offer material reduction. In spite of these benefits environmental issues connected with the manufacturing of composite materials and their disposal are of great concern.

DESIGN PHILOSOPHY

The replacement of naval structures, components and machinery made with steel, aluminium alloy and bronze with composites has been a difficult and slow process. As metals perform extremely well in most applications, designers, builders and operators have a great deal of confidence in the performance of metals. Steel can be considered as an universal construction material as its material properties does not change from place to place, from one manufacturing method to another method or one manufacturing yard to another. In the case of composite materials an indecisiveness of strength properties arise due to changes in factors like matrix selection, reinforcement selection, fibre or matrix volume selection, angle of reinforcement selection, stacking sequence of different layers etc. The factors stated above are very less in number when real scenario is considered. Hence a need for certain design philosophies which are generic in nature arises. In this study the design philosophy adopted is based on strength and sustainability of composite material.

Composite materials, as a ship hull constructional material is superior to already established materials as they possess better specific strength and specific stiffness than these conventional materials. For any material to be considered as a construction material, strength is the predominant selection criteria. When sustainability is considered composite materials are given a second thought as there is not much technological data available in this area. When compared to already established construction materials like metals, there is a conception or misconception that composite materials are not sustainable. As composite materials possess superior material properties it is the need of the hour to establish it’s superiority in the area of sustainability. At present, due to the confidence gained through experience in marine composite construction and superior strength properties, CFRP and AFRP are also used extensively along with already established composite material, GFRP. In this context there is the need to conduct a comparative study of strength and sustainability of different available composite materials. For this a two dimensional assessment of composite materials has been developed based on strength and sustainability, to assess the degree of acceptability of various composite materials as a sustainable hull construction material. This is done by constructing a strength index and a sustainability index and then both the indices are superimposed and compared. This can be considered as a general procedure that can be adopted for an array of composite materials. Song et.al.[2009] have conducted a Life Cycle Assessment (LCA) of fibre-reinforced composites manufactured using pultrusion process. All of the life cycle stages, i.e, material production, manufacturing, use, and end-of life phases, were taken into account to estimate the total energy use. Lepech et.al.[2005] have studied about increasing sustainability by the use of new materials, deliberately designed with sustainability as a primary goal.

SPECIMENS STUDIED

In the present study the laminates considered are made of all possible combinations of three commonly used fibres and three matrices in ship hull construction. The fibres used in this study of non metallic composite materials used for hull construction are Carbon(C), Glass (G) and Aramid (A) and the matrices used are Epoxy (E), Vinyl Ester (VE) and Poly Ester (PE). Accordingly nine types of non metallic hull materials are studied. The possible combinations are Carbon / Epoxy (CFRP(E)), Carbon / Vinyl Ester (CFRP(VE)), Carbon / Poly Ester (CFRP(PE)), Glass / Epoxy (GFRP(E)), Glass / Vinyl Ester (GFRP(VE)), Glass / Poly Ester (GFRP(PE)), Aramid / Epoxy (AFRP(E)), Aramid / Vinyl Ester (AFRP(VE)) and Aramid / Poly Ester (AFRP(PE)).

STRENGTH INDEX

An index is constructed by selecting varaibles according to the main theme under consideration and ranking them according to their index values. The primary variable considered to create a strength index is modulus of elasticity. *Rule of mixtures* is used to find the modulus of elasticity of composite laminates from the properties of the constituents. The analytical formulae used to find the elastic modulus of laminate in the longitudinal direction are:

$$E_1 = E_f V_f + E_m V_m \quad (1)$$

$$V_f = A_f / A \quad (2)$$

$$V_m = A_m / A \text{ or } (1 - V_f) \quad (3)$$

Values of Modulus of elasticity of the constituents i.e. fibres and matrices (Springer & Kollar 2003) are given in Table 1. Modulus of elasticity of laminates are calculated using the above rule of mixtures and is given in Table 2. Based on the elastic modulus value the strength index is created as shown in Table 3. While calculating the Strength Index, specimen with highest strength value is assigned a rank of 1 and specimen with lowest strength value is assigned a rank of 9 i.e. higher the strength or index value lower the rank.

Table 1: Material Properties of Fibres and Matrices

Fibres	E_f(GPa)	Matrices	E_m(GPa)
Glass	72	Epoxy	3.4
Carbon	234	Vinyl Ester	3.2
Aramid	124	Poly Ester	3.3

Table 2: Index Rank Based on Strength of Composite Laminates

Specimen	CFRP (E)	CFRP (VE)	CFRP (PE)	GFRP (E)	GFRP (VE)	GFRP (PE)	AFRP (E)	AFRP (VE)	AFRP (PE)
E_1(GPa)	141.76	141.68	141.72	44.56	44.48	44.52	75.76	75.68	75.72
Index Rank	1	3	2	7	9	8	4	6	5

SUSTAINABILITY INDEX

Sustainability Index is constructed by considering the life cycle of composite vessels. Life cycle of a composite vessel consists of its manufacturing phase, operation phase and disposal phase. Sustainability during operation phase is almost same for all the nine laminates materials. (Dominic & Nandakumar, 2012) In the present study manufacturing phase alone is considered. In the manufacturing phase of composite laminates, the environmental impact of manufacturing of constituent materials is considered to construct the sustainability index. Sustainability Index for the above nine specimens has been constructed by calculating the Index values for the environmental impact of manufacturing of constituent materials. Index values are calculated using the data in Table 3. Accordingly the sustainability index rank is calculated as shown in table 4. While calculating Sustainability Index, specimen with lowest environmental impact value is assigned a rank of 1 and specimen with highest environmental impact value is assigned a rank of 9 i.e. lower the environmental impact value or index value, lower the rank.

Table 3: Index Value for Environmental Impact of Manufacturing of Constituent Materials

Secondary Variables	Environmental Impact of Manufacturing of Constituent Materials											
Tertiary Variables	Fibre						Matrix					
	Embodied Energy			CO2 Emissions			Embodied Energy			CO2 Emissions		
	Carbon	Aramid	Glass	Carbon	Aramid	Glass	Epoxy	Poly Ester	Vinyl Ester	Poly Ester	Epoxy	Vinyl Ester
Rank	3	2	1	3	2	1	3	2	1	3	2	1

Table 4: Index Rank based on Sustainability of Composite Materials

Specimen	CFRP (E)	CFRP (VE)	CFRP (PE)	GFRP (E)	GFRP (VE)	GFRP (PE)	AFRP (E)	AFRP (VE)	AFRP (PE)
Fibre	6	6	6	2	2	2	4	4	4
Matrix	5	2	5	5	2	5	5	2	5
Aggregation of Fibre and Matrix	11	8	11	7	4	7	9	6	9
Index Rank	9	5	9	4	1	4	7	2	7

DESIGN FOR STRENGTH AND SUSTAINABILITY

According to Design for Strength and Sustainability philosophy a two dimensional assessment of the composite materials is done by using a Strength Index versus Sustainability Index graph (Figure 1). Sustainability Index is plotted on 'x' axis and Strength Index is plotted on 'y' axis. From the graph it can be seen that higher the strength lower the sustainability and vice versa. Indices have been prepared in such a manner that composite laminates that lie in the bottom left corner of the Strength Index versus Sustainability Index graph are to be selected as hull construction material. Thus a balance between strength and sustainability can be attained in the selection process.

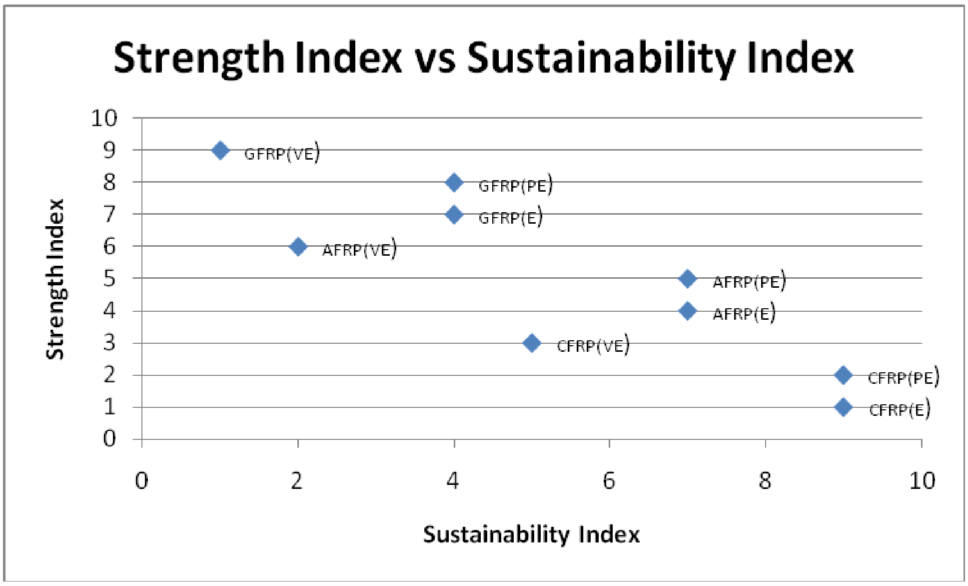

Figure 1: Composite Laminates Assessments are Given in a Two Dimensional Format. Sustainability is on 'X' Axis and Strength on 'Y' Axis. Lower Values are Preferred

CONCLUSIONS

In the present study nine composite laminates are considered. Based on the primary variable, modulus of elasticity, a strength index has been constructed. Based on the primary variable, environmental impact of the

manufacturing of constituent materials, a sustainability index has been constructed. In the indices lower rank means, higher strength or lower environmental impact. This also means lower the rank, higher the acceptability of the composite laminates. Using these two indices a two dimensional assessment of composite laminates has been conducted. In this study both the indices have been superimposed to get strength versus sustainability graph. Analysis of this graph is the core of the design philosophy, ‘Design for strength and sustainability’. Accordingly a composite material having the least strength and sustainability index needs to be selected as the best one. Among the composite laminates considered in this study, the one that has been selected for ship hull construction is Carbon Fibre Reinforced Polymer - CFRP (VE). The strength and sustainability indices have a value below or equal to the average value.

This procedure can be extended to any number of composites in the marine area or to composites that has application in other areas. In the present study strength and sustainability indices are prepared by considering less number of parameters. More parameters can be included to attain a more reliable assessment. For that more research is needed in the strength properties like fatigue, low cycle fatigue, impact etc. and sustainability studies need to be conducted in the full manufacturing phase and disposal phase of composite laminates.

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